Use of TerraSAR-X data to retrieve soil moisture over bare soil agricultural fields

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Use of TerraSAR-X Data to Retrieve Soil Moisture Over Bare Soil Agricultural Fields

Nicolas Baghdadi, Maelle Aubert, and Mehrez Zribi

***Abstract*—The retrieval of the bare soil moisture content from TerraSAR-X data is discussed using empirical approaches. Two cases were evaluated: 1) one image at low or high incidence angle and 2) two images, one at low incidence and one at high incidence. This study shows by using three databases collected between 2008 and 2010 over two study sites in France (Orgeval and Villamblain) that TerraSAR-X is a good remote sensing tool for the retrieving of surface soil moisture with accuracy of about 3% (rmse). Moreover, the accuracy of the soil moisture estimate does not improve when two incidence angles (26°–28° or 50°–52°) are used instead of only one. When compared with the result obtained with a high incidence angle (50°–52°), the use of low incidence angle (26°–28°) does not enable a significant improvement in estimating soil moisture (about 1%).**

***Index Terms*—Soil moisture, TerraSAR-X images.**

I. Introduction

RADAR SIGNAL is a function of soil moisture and surface roughness in the case of bare soil. The possibility of retrieving these soil parameters was little investigated from X-band synthetic aperture radar (SAR). However, many studies were carried out by using C-band radar data (e.g., [1]–[4]). With the launch of satellites using the X-band (∼9.6 GHz), such as TerraSAR-X and COSMO-SkyMed, the use of X-band data to derive soil parameters became possible. A radar configuration that minimizes the effects of surface roughness is recommended for a better estimate of soil moisture when using only one incidence angle. The optimal radar incidences in C-band for the retrieval of soil moisture are smaller than 35° [4].

Soil moisture estimation from SAR images is carried out by using physical or statistical models. Physical approach consists in using a physical model, such as the integral equation model [5], to predict the radar backscattering coefficient from SAR and soil parameters (wavelength, polarization, incidence angle, surface roughness, and soil dielectric constant). Statistical models based on experimental measurements are also often used in soil moisture estimation. For bare soils, the increase of radar signal (σ°) is supposed to be linear with the volumetric soil moisture for values between 5% and 35% [6]. Moreover, σ° increases with soil surface roughness and follows an exponential or logarithmic behavior (e.g., [4] and [7]).

Fig. 1. Location of study sites. (1) Orgeval. (2) Villamblain.

Very few studies analyzed the sensitivity of TerraSAR-X data to bare soil surface parameters. Baghdadi *et al.* [8] have observed that the radar signal at X-band is slightly more sensitive to surface roughness at high incidence angle than at low incidence angle. The difference observed between radar signals reflected by the roughest and smoothest areas increases with the radar wavelength. Moreover, results showed that the sensitivity of radar signal to surface roughness is better with PALSAR in L-band than with TerraSAR-X in X-band and that the C- and X-bands are similar sensitivity results. In this letter, only *in situ* soil moisture measurements in very wet conditions between 25% and 40% are available. Results obtained showed that the backscattering coefficient at X-band is stable when the moisture content ranges between 25% and 35% and that it decreases beyond this threshold.

Aubert *et al.* [9] have showed that the sensitivity of the TerraSAR-X signal to soil moisture is very important at low and high incidence angles. In comparison to results published with C-band SAR data, this sensitivity of the radar signal to soil moisture is higher in X-band. The second important result concerns the potential of the fine spatial resolution of TerraSAR (1 m) in the detection of soil moisture variations at the within-plot scale. The spatial distribution of slaking crust could be detected when soil moisture variation is observed between soil crusted and soil without crust. Indeed, areas covered by slaking crust could have greater soil moisture and, consequently, a greater backscattering signal than soils without crust.

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N. Baghdadi and M. Aubert are with UMR TETIS, CEMAGREF, 34093 Montpellier, France (e-mail: nicolas.baghdadi@teledetection.fr; maelle.aubert@teledetection.fr).

M. Zribi is with Centre d'Etudes Spatiales de la BIOsphère, Institut de Recherche pour le Développement, 31401 Toulouse, France.

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TABLE I
CHARACTERISTICS OF TERRASAR-X IMAGES AND SUMMARY OF GROUND-TRUTH MEASUREMENTS (mv, rms, AND L)

Date dd-mm-yy	Site	Pol.-Inc.	Fields number	mv (%) (min;max)	rms (cm) (min;max)	L (cm) (min;max)
06-02-08	Villamblain	HH-52°	8	(27 ; 34)	(1.3 ; 3.1)	(4.5 ; 9.1)
07-02-08	Villamblain	HH-28°	8	(27 ; 34)	(1.3 ; 3.1)	(4.5 ; 9.1)
12-02-08	Orgeval	HH-50°	6	(31 ; 36)	(1.8 ; 3.3)	(5.0 ; 9.3)
13-02-08	Orgeval	HH-26°	6	(31 ; 35)	(1.8 ; 3.3)	(5.0 ; 9.3)
17-03-09	Orgeval	HH-26°	7	(25 ; 32)	(1.7 ; 2.3)	(4.8 ; 6.9)
18-03-09	Orgeval	HH-50°	7	(24 ; 30)	(1.7 ; 2.3)	(4.8 ; 6.9)
25-03-09	Orgeval	HH-50°	3	(28 ; 29)	(2.0 ; 2.7)	(4.8 ; 5.7)
26-03-09	Orgeval	HH-26°	3	(24 ; 31)	(2.0 ; 2.7)	(4.8 ; 5.7)
08-04-09	Orgeval	HH-26°	6	(17 ; 26)	(1.1 ; 2.1)	(3.7 ; 6.0)
09-04-09	Orgeval	HH-50°	6	(15 ; 26)	(1.1 ; 2.1)	(3.7 ; 6.0)
01-03-10	Orgeval	HH-50°	6	(33 ; 40)	(1.9 ; 2.9)	(5.9 ; 7.5)
02-03-10	Orgeval	HH-26°	6	(33 ; 37)	(1.9 ; 2.9)	(5.9 ; 7.5)
12-03-10	Orgeval	HH-50°	7	(13 ; 25)	(1.1 ; 2.6)	(4.6 ; 7.0)
13-03-10	Orgeval	HH-26°	7	(15 ; 22)	(1.1 ; 2.6)	(4.6 ; 7.0)

At least one research question remained open. It concerns the precision of the soil moisture estimates in bare agricultural soils. The objective of this study is to examine the potential of TerraSAR-X data for retrieving volumetric soil moisture over bare soils. This work evaluates if the use of two incidence angles at X-band [one low (26°–28°) and one high (50°–52°)] improves the accuracy of the estimate of surface soil moisture in comparison to only one incidence (low or high). TerraSAR-X sensor has the advantage to acquire on the same study site image pairs at low and high incidence angles within one day. The goal of this work is to compare the findings with C- and X-band data. At C-band, several studies have shown that the use of two incidence angles provides distinct improvement in the soil moisture estimate, in comparison with results obtained using a single incidence (e.g., [1], [2], and [4]). Moreover, low incidence angle is better than the high incidence angle for estimating soil moisture with C-band SAR data. This letter investigates this research question.

II. STUDY AREA AND DATA SET

A. Study Site

Data were acquired over two mainly agricultural sites (Fig. 1). The Villamblain site is located in the south of Paris, France (latitude $48°01'$ N and longitude $1°35'$ E) with soil composed of 30% clay, 60% silt, and 10% sand. The second site is situated in the Orgeval watershed, located in the east of Paris, France (latitude $48°51'$ N and longitude $3°07'$ E). The soil has a loamy texture, composed of 78% silt, 17% clay, and 5% sand. Both of these two sites are very flat.

During the period of February–April (our SAR acquisitions), the main crops are wheat and colza. They cover approximately 50% of the agricultural area. The remaining surface corresponds to plowed soils awaiting future cultivation (corn and potato).

B. TerraSAR-X Images

Fourteen TerraSAR-X images (X-band ∼9.65 GHz) were acquired during the years of 2008, 2009, and 2010 (Table I). The radar data are available in HH polarization, with incidence angles (θ) of 26°, 28°, 50°, and 52°. The imaging mode used was spotlight with a pixel spacing of 1 m. Radiometric calibration using multilook ground range detected TerraSAR-X images was first carried out using the following equation [10]:

$$\sigma_i^\circ(\mathrm{dB}) = \log_{10}\left(Ks \cdot DN_i^2 - NEBN\right) + 10\log_{10}(\sin\theta_i). \tag{1}$$

This equation transforms the amplitude of backscattered signal for each pixel (DN_i) into a backscattering coefficient (σ°) in decibels. Ks is the calibration coefficient, and $NEBN$ is the noise equivalent beta naught. All TerraSAR-X images were then georeferenced using GPS points with a root-mean-square error of the control points of approximately one pixel (i.e., 1 m). This coregistration error was overcome by removing two boundary pixels from each training plot relative to the limits defined by the GPS control points. The mean backscattering coefficients were calculated from calibrated SAR images by averaging the linear σ° values of all pixels within reference fields.

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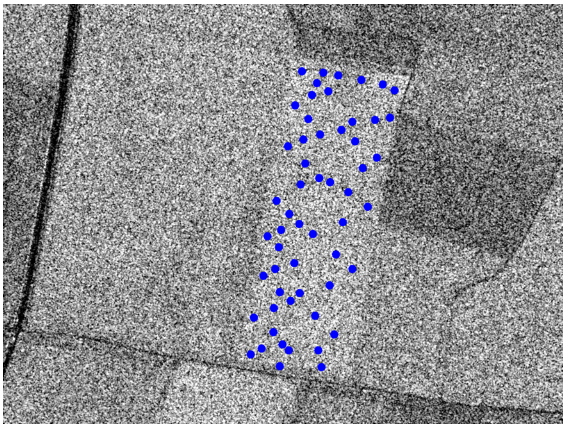

Fig. 2. Example of volumetric soil moisture measurements taken on a reference field.

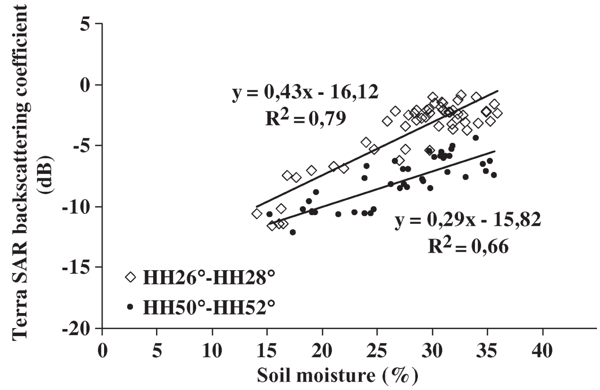

Fig. 3. TerraSAR-X signal versus volumetric soil moisture (measured at a depth of 5 cm). Each point corresponds to the average backscattering coefficient in decibels for one reference field. Thirty points are used for each of the two configurations HH26°–28° and HH50°–52° (data sets of 2008 and 2009).

C. Field Data

Simultaneously with TerraSAR-X acquisition, field measurements of soil moisture and surface roughness have been achieved on several bare soil reference fields of at least 2 ha. In the case of TerraSAR-X in spotlight mode (pixel spacing of 1 m), this corresponds to a surface of 20 000 pixels or more.

The volumetric water content at field scale was assumed to be equal to the mean value estimated from several samples (20–40 measurements per field; Fig. 2) collected from the top 5 cm of soil using the gravimetric method. The soil moistures range from 13% to 40%.

In most studies of microwave measurements carried out over bare soils, the experimental relationship between soil moisture and backscattering coefficient is provided by mean volumetric water contents measured to a soil depth, generally 0–5 cm or 0–10 cm. Indeed, only some studies using theory results are available at X-band. These studies suggest a penetration depth maybe lower than 5 cm. No experimental measurements are made in field condition, and the low penetration depth of X-band is only based on theoretical study. Therefore, the penetration depth of the X-band is not yet well known.

Roughness measurements were made using needle profilometers (1 m long and with 2-cm sampling intervals). Ten roughness profiles were sampled for each training field (parallel and perpendicular to the row direction). From these measurements, the two roughness parameters, i.e., root mean square (rms) surface height and correlation length (L), were calculated using the mean of all correlation functions. The rms surface heights range from 1.1 to 3.3 cm, and the correlation length (L) varies from 2.3 cm in sown fields to 9.3 cm in plowed fields.

III. Methodology

The retrieval of soil moisture from TerraSAR-X images by means of empirical approaches requires the development of experimental relationships between $\sigma^{\circ}_{\mathrm{TerraSAR-X}}$ and the measured soil moisture. TerraSAR data acquired in two configurations of incidence angles ($\sim 26^{\circ}$ and $\sim 50^{\circ}$) were used with ground measurements conducted over bare soil. The sensitivity of TerraSAR signal to soil moisture is the greatest for low incidence angle (0.43 dB/% for 26°–28° and 0.29 dB/% for 50°–52°; Fig. 3). For a confidence level of 95%, there are significant relationships between the TerraSAR-X backscattering coefficient and the *in situ* soil moisture because the p-values are much less than 0.05 ($p\text{-}value < 2.2 \times 10^{-16}$ for HH26°–28° **AQ8** and $p\text{-}value = 1.52 \times 10^{-10}$ for HH50°–52°).

Studies using C-band (ERS, RADARSAT, ASAR, etc.) **AQ9** showed lower sensitivities between radar signal and soil moisture, between 0.2 and 0.3 dB/% for low incidence angles and about 0.1 dB/% for high incidence angles (e.g., [2] and [11]–[13]).

The objective of this study is to analyze the influence of incidence angle on the accuracy of the soil moisture estimate. Configurations in HH polarization with single incidence angle (26°–28° or 50°–52°) were studied. Next, multi-incidence TerraSAR-X images acquired at both low and high θ values with one-day-spaced dates and only minor variations in soil characteristics were used to analyze the possible improvement in the soil moisture estimates when two incidences are used.

The empirical relationship between the radar backscattering coefficient (σ°) and the volumetric soil moisture (mv) for bare soil surfaces without taking into account the rms surface height is given by (e.g., [14]; Fig. 3)

$$\sigma^{\circ}_{\mathrm{dB}} = f(mv, \theta)_{\mathrm{dB}} = \delta mv + \xi. \quad (2)$$

This simplified relationship is valid for mv values between 5% and 35% [6]. The coefficient δ is dependent on SAR parameters (radar wavelength, incidence angle, and polarization), while the coefficient ξ is controlled by SAR parameters and surface roughness. Experimental data of σ° and mv show slope δ values of about 0.43 dB/% for HH26°–28° and 0.29 dB/% for HH50°–52°.

The relationship obtained between σ° and the rms *height* independent of row direction, correlation length, and soil moisture could be written as an exponential relationship of the form $\sigma^{\circ}_{\mathrm{dB}} = g(rms, \theta)_{\mathrm{dB}} = \mu e^{-krms} + c$ [15], [16] or a logarithmic relationship of the form $\sigma^{\circ}_{\mathrm{dB}} = g(rms, \theta)_{\mathrm{dB}} = \mu \ln(rms) + c$ [1]. **AQ10**

With taking into account of both soil roughness and soil moisture, the radar signal in decibel scale may be written as

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TABLE II
INVERSION MODELS FOR ESTIMATING SOIL MOISTURE AND STATISTICS ON THE VALIDATION OF THESE MODELS

TerraSAR-X data - HH	Calibration phase Model	R^2	Validation phase		
			Bias	std	RMSE
26°-28°	mv (%) = 2.31 $\sigma°_{dB}$ + 37.19	0.79	0.52	2.76	2.81
50°-52°	mv (%) = 3.43 $\sigma°_{dB}$ + 54.30	0.66	2.95	2.83	4.09
26°-28° and 50°-52°	mv (%) = 1.67 $\sigma°_{dB}$ (θ_{low}) + 0.55 $\sigma°_{dB}$ (θ_{high}) + 38.22	0.69	1.65	2.46	2.91

the sum of two functions that describe the dependence of the radar signal on soil moisture (f: linear) and surface roughness (g: exponential) (e.g., [1] and [4])

$$\sigma^\circ_{\mathrm{dB}} = f(mv,\theta)_{\mathrm{dB}} + g(rms,\theta)_{\mathrm{dB}} = \delta, mv + \mu, e^{-krms} + \tau \tag{3}$$

where k is the radar wavenumber ($\sim 2\ \mathrm{cm}^{-1}$ for TerraSAR-X).

This equation neglects the effect of the correlation length L on the backscattering coefficient. To take account of the correlation length, Zribi and Deschambre [1] proposed a new roughness parameter Zs, *defined by* rms^2/L, which is the product of the rms surface height and the slope of the soil surface (rms/L). Thus, the empirical model linking σ° and Zs could be written as $\sigma^\circ_{\mathrm{dB}} = \delta mv + \eta e^{-kZs} + \psi$.

In the case of one SAR image characterized by one incidence ($\theta = 26°$–$28°$ or $50°$–$52°$), inversion model is written as follows:

$$mv = \alpha\sigma^\circ(\theta) + \beta. \tag{4}$$

The use of two incidence angles eliminates the effects of roughness and thus allows linking the backscattering coefficient to the soil moisture only. For two images acquired with low and high incidence angles, the estimate of soil moisture can be obtained by solving (3) for two incidences (substituting the e^{-krms} of $\sigma^\circ(\theta_{\mathrm{low}})$ into $\sigma^\circ(\theta_{\mathrm{high}})$

$$mv = \alpha\sigma^\circ(\theta_{\mathrm{low}}) + \beta\sigma^\circ(\theta_{\mathrm{high}}) + \gamma. \tag{5}$$

α and β depend on δ and μ, whereas γ is a function of δ, μ, and τ (in both incidence angles).

The form of (5) should be the same if the Zs parameter was used.

The empirical models given in (4) and (5) were then fitted to experimental data acquired in 2008 and 2009 by using the least squares method (cf. Table II). The validation of these models was tested in using the data set of 2010 (13 points for each of the two configurations HH26° and HH50°). The inputs are the mean backscattering coefficients in decibels calculated for each reference field.

IV. RESULTS AND DISCUSSION

The inversion procedures were applied in order to retrieve soil moisture. The results obtained in the validation phase with one low incidence show inversion errors in the estimation of mv of about 3% for incidence angles. The use of high incidences (50°–52°) gives slightly poorer results with an rmse of about 4%. The accuracy of the soil moisture estimate remains unchanged by using TerraSAR-X multi-incidence data (both low and high incidence angles) with an rmse of about 3% (Table II). Fig. 4 shows the good agreement between estimated and measured mv values.

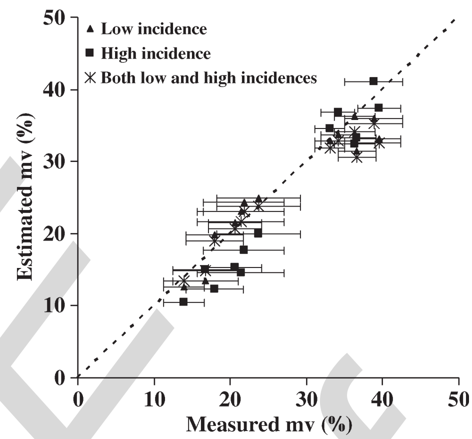

Fig. 4. Comparison between the estimated mv values and those measured. The error bars on the measured soil moisture values correspond to one standard deviation.

In contrast, large errors in the retrieved soil moisture were observed at C-band for a single incidence angle (rmses of about 6% for 20° and 9% for 40°) [4]. This is due to the fact that the radar signal is much more sensitive to surface roughness at high radar wavelength. The accuracy is strongly improved with the use of both low and high incidences (rmse of about 3.5%) (e.g., [1], [2], and [4]).

The dependence of the radar signal at X-band on surface roughness in agricultural areas was described as weak by several works ([8], [14], and [17]). Results of these studies show that the influence of surface roughness on the radar signal increases with increasing radar wavelength. Moreover, this dependence is mainly significant for low levels of roughness. At X-band, Baghdadi *et al.* [4], [8] showed that the sensitivity of σ° to surface roughness becomes weak for $rms > 1$ cm. Thus, the effect of surface roughness on radar signal becomes weak in X-band, which improves the estimates of soil moisture, particularly for $rms > 1$ cm. Moreover, the multi-incidence approaches become less effective because the effect of surface roughness that we try to eliminate is relatively weak at X-band compared to C-band.

TABLE III
TERRASAR-X COVERAGE SIMULATION FOR ORGEVAL SITE BETWEEN SEPTEMBER 2 AND 12, 2010 (ORBIT CYCLE)

Time	02 sep.	03 sep.	04 sep.	05 sep.	06 sep.	07 sep.	08 sep.	09 sep.	10 sep.	11 sep.	12 sep.
θ (°)	-	39	58	50	26	-	26	50	58	39	-

V. CONCLUSION

This study examined the potential of TerraSAR-X data for estimating soil moisture (mv) over bare soils. TerraSAR-X images collected between 2008 and 2010 over two study sites in France were used. SAR images were acquired at HH polarization and for incidence angles of 26°, 28°, 50°, and 52°. The goal of this work was to compare estimates of mv obtained from various incidence configurations and to find the best sensor configuration in incidence angle for measuring the bare soil moisture.

This study tested empirical models for soil moisture inversion from one incidence (low or high) and multi-incidence TerraSAR-X data (both low and high incidences). The results of this study may be summarized as follows.

1) For a single incidence, the retrieval algorithm performed very well for low and high incidence angles. The rmses for the soil moisture estimate are about 3% for 26°–28° and 4% for 50°–52°.
2) The accuracy of the soil moisture estimate does not improve when two incidence angles (rmse is about 3%) are used.

These results appear promising for the development of simplified algorithms for retrieving soil moisture from TerraSAR-X data and for monitoring temporal moisture changes. Table III lists the different observation possibilities for the Orgeval study site within one orbit cycle (11 days). This site could be imaged 8 times within 11 days (two images for each following incidence: $\sim$ 26°, 39°, 50°, and 58°) and 24 times within one month. The soil moisture mapping frequency with low incidence angle (26°) or with both low and high incidence angles (26° and 50°) is possible six times within one month. The incidence of 39° can also be used, which would increase to 12 the TerraSAR-X scene number within one month. This very short revisit time makes TerraSAR-X a very useful source for the soil moisture mapping. Moreover, the increase in the acquisition frequency is much awaited for the soil moisture data assimilation in hydrological modeling.

In addition, the very high spatial resolution (metric) of the TerraSAR-X sensor is also very promising for local estimation of soil moisture at the within agricultural field scale. It offers a great potential in terms of improving the quality of soil moisture mapping for catchment areas where the parcels are of small size.

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REFERENCES

[1] M. Zribi and M. Dechambre, "A new empirical model to retrieve soil moisture and roughness from C-band radar data," *Remote Sens. Environ.*, vol. 84, no. 1, pp. 42–52, Jan. 2003.

[2] H. S. Srivastava, P. Patel, M. L. Manchanda, and S. Adiga, "Use of multi-incidence angle RADARSAT-1 SAR data to incorporate the effect of surface roughness in soil moisture estimation," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 7, pp. 1638–1640, Jul. 2003.

[3] Y. Oh, "Quantitative retrieval of soil moisture content and surface roughness from multipolarized radar observations of bare soil surfaces," *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 3, pp. 596–601, Mar. 2004.

[4] N. Baghdadi, N. Holah, and M. Zribi, "Soil moisture estimation using multi-incidence and multi-polarization ASAR SAR data," *Int. J. Remote Sens.*, vol. 27, no. 10, pp. 1907–1920, 2006.

[5] A. K. Fung, *Microwave Scattering and Emission Models and Their Applications*. Boston, MA: Artech House, 1994, 573 pages.

[6] H. Holah, N. Baghdadi, M. Zribi, A. Bruand, and C. King, "Potential of ASAR/ENVISAT for the characterisation of soil surface parameters over bare agricultural fields," *Remote Sens. Environ.*, vol. 96, no. 1, pp. 78–86, May 2005.

[7] F. T. Ulaby, P. P. Batlivala, and M. C. Dobson, "Microwave backscatter dependence on surface roughness, soil moisture, and soil texture: Part I—Bare soil," *IEEE Trans. Geosci. Electron.*, vol. GE-16, no. 4, pp. 286–295, Oct. 1978.

[8] N. Baghdadi, M. Zribi, C. Loumagne, P. Ansart, and T. Paris Anguela, "Analysis of TerraSAR-X data and their sensitivity to soil surface parameters over bare agricultural fields," *Remote Sens. Environ.*, vol. 112, no. 12, pp. 4370–4379, Dec. 2008.

[9] M. Aubert, N. Baghdadi, M. Zribi, A. Douaoui, C. Loumagne, F. Baup, M. El Hajj, and S. Garrigues, "Analysis of TerraSAR-X data sensitivity to bare soil moisture, roughness, composition and soil crust," *Remote Sens. Environ.*, vol. 115, no. 8, pp. 1801–1810, Aug. 2011.

[10] T. Fritz, TerraSAR-X Ground Segment Level 1b Product Format Specification (10.12.2007), p. 257, 2007, Issue, 1.3, Doc.: TX-GS-DD-3307. [Online]. Available: http://www.dlr.de/tsx/documentation/TX-GS-DD-3307_Level-1b-Product-Format-Specification_1.3.pdf AQ11

[11] N. Baghdadi, O. Cerdan, M. Zribi, V. Auzet, F. Darboux, M. El Hajj, and R. Bou Kheir, "Operational performance of current synthetic aperture radar sensors in mapping soil surface characteristics: Application to hydrological and erosion modeling," *Hydrol. Process.*, vol. 22, no. 1, pp. 9–20, Jan. 2008.

[12] S. Le Hégarat-Mascle, M. Zribi, F. Alem, A. Weisse, and C. Loumagne, "Soil moisture estimation from ERS/SAR data: Toward an operational methodology," *IEEE Trans. Geosci. Remote Sens.*, vol. GRS-24, no. 12, pp. 2647–2658, Dec. 2002.

[13] A. Quesney, S. Le Hégarat-Mascle, O. Taconet, D. Vidal-Madjar, J. P. Wingneron, C. Loumagne, and M. Normand, "Estimation of watershed soil moisture index from ERS/SAR data," *Remote Sens. Environ.*, vol. 72, no. 3, pp. 290–303, Jun. 2000.

[14] F. T. Ulaby, R. K. Moore, and A. K. Fung, *Microwave Remote Sensing, Active and Passive, From Theory to Applications*, vol. 3. Norwood, MA: Artech House, 1986, 1098 pages.

[15] Y. Oh, K. Sarabandi, and F. T. Ulaby, "An empirical model and an inversion technique for radar scattering from bare soil surfaces," *IEEE Trans. Geosci. Remote Sens.*, vol. 30, no. 2, pp. 370–381, Mar. 1992.

[16] N. Baghdadi, C. King, A. Bourguignon, and A. Remond, "Potential of ERS and RADARSAT data for surface roughness monitoring over bare agricultural fields: Application to catchments in Northern France," *Int. J. Remote Sens.*, vol. 23, no. 17, pp. 3427–3442, 2002.

[17] N. Baghdadi, N. Holah, P. Dubois, L. Prévot, S. Hosford, A. Chanzy, X. Dupuis, and M. Zribi, "Discrimination potential of X-band polarimetric SAR data," *Int. J. Remote Sens.*, vol. 25, no. 22, pp. 4933–4942, 2004.

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AQ1 = “In” was changed to “by.” Please check if the original thought was retained.
AQ2 = Please provide the expanded form of the acronym “COSMO-SkyMed.”
AQ3 = Please provide the expanded form of the acronym “ORFEO.”
AQ4 = “French Space Study Center” was changed to “National Space Study Center.” Please check if appropriate.
AQ5 = Please provide the expanded form of the acronym “UMR TETIS.”
AQ6 = The acronyms “CESBIO” and “IRD” were defined as “Centre d’Etudes Spatiales de la BIOsphère” and “Institut de Recherche pour le Développement,” respectively. Please check if appropriate.
AQ7 = Please provide the expanded form of the acronym “PALSAR.”
AQ8 = All occurrences of “$2.2e^{-16}$” were changed to “$< 2.2 \times 10^{-16}$.” Please check if appropriate.
AQ9 = Please provide the expanded forms of the acronyms “ERS,” “RADARSAT,” and “ASAR.”
AQ10 = This sentence was reworded for clarity. Please check if the original thought was retained.
AQ11 = Please check the URL provided in Ref. [10]. Page was not found.

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Use of TerraSAR-X Data to Retrieve Soil Moisture Over Bare Soil Agricultural Fields

Nicolas Baghdadi, Maelle Aubert, and Mehrez Zribi

***Abstract*—The retrieval of the bare soil moisture content from TerraSAR-X data is discussed using empirical approaches. Two cases were evaluated: 1) one image at low or high incidence angle and 2) two images, one at low incidence and one at high incidence. This study shows by using three databases collected between 2008 and 2010 over two study sites in France (Orgeval and Villamblain) that TerraSAR-X is a good remote sensing tool for the retrieving of surface soil moisture with accuracy of about 3% (rmse). Moreover, the accuracy of the soil moisture estimate does not improve when two incidence angles (26°–28° or 50°–52°) are used instead of only one. When compared with the result obtained with a high incidence angle (50°–52°), the use of low incidence angle (26°–28°) does not enable a significant improvement in estimating soil moisture (about 1%).**

***Index Terms*—Soil moisture, TerraSAR-X images.**

I. Introduction

RADAR SIGNAL is a function of soil moisture and surface roughness in the case of bare soil. The possibility of retrieving these soil parameters was little investigated from X-band synthetic aperture radar (SAR). However, many studies were carried out by using C-band radar data (e.g., [1]–[4]). With the launch of satellites using the X-band (∼9.6 GHz), such as TerraSAR-X and COSMO-SkyMed, the use of X-band data to derive soil parameters became possible. A radar configuration that minimizes the effects of surface roughness is recommended for a better estimate of soil moisture when using only one incidence angle. The optimal radar incidences in C-band for the retrieval of soil moisture are smaller than 35° [4].

Soil moisture estimation from SAR images is carried out by using physical or statistical models. Physical approach consists in using a physical model, such as the integral equation model [5], to predict the radar backscattering coefficient from SAR and soil parameters (wavelength, polarization, incidence angle, surface roughness, and soil dielectric constant). Statistical models based on experimental measurements are also often used in soil moisture estimation. For bare soils, the increase of radar signal ($\sigma°$) is supposed to be linear with the volumetric soil moisture for values between 5% and 35% [6]. Moreover, $\sigma°$ increases with soil surface roughness and follows an exponential or logarithmic behavior (e.g., [4] and [7]).

Fig. 1. Location of study sites. (1) Orgeval. (2) Villamblain.

Very few studies analyzed the sensitivity of TerraSAR-X data to bare soil surface parameters. Baghdadi *et al.* [8] have observed that the radar signal at X-band is slightly more sensitive to surface roughness at high incidence angle than at low incidence angle. The difference observed between radar signals reflected by the roughest and smoothest areas increases with the radar wavelength. Moreover, results showed that the sensitivity of radar signal to surface roughness is better with PALSAR in L-band than with TerraSAR-X in X-band and that the C- and X-bands are similar sensitivity results. In this letter, only *in situ* soil moisture measurements in very wet conditions between 25% and 40% are available. Results obtained showed that the backscattering coefficient at X-band is stable when the moisture content ranges between 25% and 35% and that it decreases beyond this threshold.

Aubert *et al.* [9] have showed that the sensitivity of the TerraSAR-X signal to soil moisture is very important at low and high incidence angles. In comparison to results published with C-band SAR data, this sensitivity of the radar signal to soil moisture is higher in X-band. The second important result concerns the potential of the fine spatial resolution of TerraSAR (1 m) in the detection of soil moisture variations at the within-plot scale. The spatial distribution of slaking crust could be detected when soil moisture variation is observed between soil crusted and soil without crust. Indeed, areas covered by slaking crust could have greater soil moisture and, consequently, a greater backscattering signal than soils without crust.

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N. Baghdadi and M. Aubert are with UMR TETIS, CEMAGREF, 34093 Montpellier, France (e-mail: nicolas.baghdadi@teledetection.fr; maelle.aubert@teledetection.fr).

M. Zribi is with Centre d'Etudes Spatiales de la BIOsphère, Institut de Recherche pour le Développement, 31401 Toulouse, France.

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TABLE I
CHARACTERISTICS OF TERRASAR-X IMAGES AND SUMMARY OF GROUND-TRUTH MEASUREMENTS (mv, rms, AND L)

Date dd-mm-yy	*Site*	*Pol.-Inc.*	*Fields number*	*mv (%) (min;max)*	*rms (cm) (min;max)*	*L (cm) (min;max)*
06-02-08	*Villamblain*	*HH-52°*	*8*	*(27 ; 34)*	*(1.3 ; 3.1)*	*(4.5 ; 9.1)*
07-02-08	*Villamblain*	*HH-28°*	*8*	*(27 ; 34)*	*(1.3 ; 3.1)*	*(4.5 ; 9.1)*
12-02-08	*Orgeval*	*HH-50°*	*6*	*(31 ; 36)*	*(1.8 ; 3.3)*	*(5.0 ; 9.3)*
13-02-08	*Orgeval*	*HH-26°*	*6*	*(31 ; 35)*	*(1.8 ; 3.3)*	*(5.0 ; 9.3)*
17-03-09	*Orgeval*	*HH-26°*	*7*	*(25 ; 32)*	*(1.7 ; 2.3)*	*(4.8 ; 6.9)*
18-03-09	*Orgeval*	*HH-50°*	*7*	*(24 ; 30)*	*(1.7 ; 2.3)*	*(4.8 ; 6.9)*
25-03-09	*Orgeval*	*HH-50°*	*3*	*(28 ; 29)*	*(2.0 ; 2.7)*	*(4.8 ; 5.7)*
26-03-09	*Orgeval*	*HH-26°*	*3*	*(24 ; 31)*	*(2.0 ; 2.7)*	*(4.8 ; 5.7)*
08-04-09	*Orgeval*	*HH-26°*	*6*	*(17 ; 26)*	*(1.1 ; 2.1)*	*(3.7 ; 6.0)*
09-04-09	*Orgeval*	*HH-50°*	*6*	*(15 ; 26)*	*(1.1 ; 2.1)*	*(3.7 ; 6.0)*
01-03-10	*Orgeval*	*HH-50°*	*6*	*(33 ; 40)*	*(1.9 ; 2.9)*	*(5.9 ; 7.5)*
02-03-10	*Orgeval*	*HH-26°*	*6*	*(33 ; 37)*	*(1.9 ; 2.9)*	*(5.9 ; 7.5)*
12-03-10	*Orgeval*	*HH-50°*	*7*	*(13 ; 25)*	*(1.1 ; 2.6)*	*(4.6 ; 7.0)*
13-03-10	*Orgeval*	*HH-26°*	*7*	*(15 ; 22)*	*(1.1 ; 2.6)*	*(4.6 ; 7.0)*

At least one research question remained open. It concerns the precision of the soil moisture estimates in bare agricultural soils. The objective of this study is to examine the potential of TerraSAR-X data for retrieving volumetric soil moisture over bare soils. This work evaluates if the use of two incidence angles at X-band [one low (26°–28°) and one high (50°–52°)] improves the accuracy of the estimate of surface soil moisture in comparison to only one incidence (low or high). TerraSAR-X sensor has the advantage to acquire on the same study site image pairs at low and high incidence angles within one day. The goal of this work is to compare the findings with C- and X-band data. At C-band, several studies have shown that the use of two incidence angles provides distinct improvement in the soil moisture estimate, in comparison with results obtained using a single incidence (e.g., [1], [2], and [4]). Moreover, low incidence angle is better than the high incidence angle for estimating soil moisture with C-band SAR data. This letter investigates this research question.

II. STUDY AREA AND DATA SET

A. *Study Site*

Data were acquired over two mainly agricultural sites (Fig. 1). The Villamblain site is located in the south of Paris, France (latitude $48°01'$ N and longitude $1°35'$ E) with soil composed of 30% clay, 60% silt, and 10% sand. The second site is situated in the Orgeval watershed, located in the east of Paris, France (latitude $48°51'$ N and longitude $3°07'$ E). The soil has a loamy texture, composed of 78% silt, 17% clay, and 5% sand. Both of these two sites are very flat.

During the period of February–April (our SAR acquisitions), the main crops are wheat and colza. They cover approximately 50% of the agricultural area. The remaining surface corresponds to plowed soils awaiting future cultivation (corn and potato).

B. *TerraSAR-X Images*

Fourteen TerraSAR-X images (X-band ∼9.65 GHz) were acquired during the years of 2008, 2009, and 2010 (Table I). The radar data are available in HH polarization, with incidence angles (θ) of 26°, 28°, 50°, and 52°. The imaging mode used was spotlight with a pixel spacing of 1 m. Radiometric calibration using multilook ground range detected TerraSAR-X images was first carried out using the following equation [10]:

$$\sigma_i^\circ(\mathrm{dB}) = \log_{10}\left(Ks \cdot DN_i^2 - NEBN\right) + 10\log_{10}(\sin\theta_i). \tag{1}$$

This equation transforms the amplitude of backscattered signal for each pixel (DN_i) into a backscattering coefficient (σ°) in decibels. Ks is the calibration coefficient, and $NEBN$ is the noise equivalent beta naught. All TerraSAR-X images were then georeferenced using GPS points with a root-mean-square error of the control points of approximately one pixel (i.e., 1 m). This coregistration error was overcome by removing two boundary pixels from each training plot relative to the limits defined by the GPS control points. The mean backscattering coefficients were calculated from calibrated SAR images by averaging the linear σ° values of all pixels within reference fields.

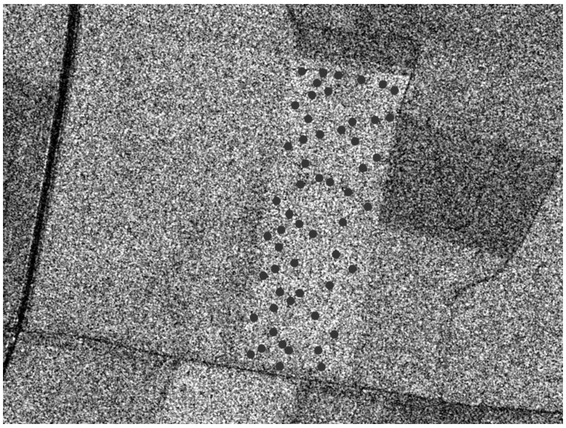

Fig. 2. Example of volumetric soil moisture measurements taken on a reference field.

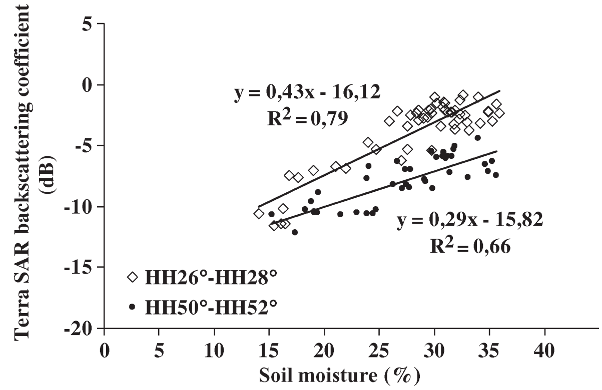

Fig. 3. TerraSAR-X signal versus volumetric soil moisture (measured at a depth of 5 cm). Each point corresponds to the average backscattering coefficient in decibels for one reference field. Thirty points are used for each of the two configurations HH26°–28° and HH50°–52° (data sets of 2008 and 2009).

C. Field Data

Simultaneously with TerraSAR-X acquisition, field measurements of soil moisture and surface roughness have been achieved on several bare soil reference fields of at least 2 ha. In the case of TerraSAR-X in spotlight mode (pixel spacing of 1 m), this corresponds to a surface of 20 000 pixels or more.

The volumetric water content at field scale was assumed to be equal to the mean value estimated from several samples (20–40 measurements per field; Fig. 2) collected from the top 5 cm of soil using the gravimetric method. The soil moistures range from 13% to 40%.

In most studies of microwave measurements carried out over bare soils, the experimental relationship between soil moisture and backscattering coefficient is provided by mean volumetric water contents measured to a soil depth, generally 0–5 cm or 0–10 cm. Indeed, only some studies using theory results are available at X-band. These studies suggest a penetration depth maybe lower than 5 cm. No experimental measurements are made in field condition, and the low penetration depth of X-band is only based on theoretical study. Therefore, the penetration depth of the X-band is not yet well known.

Roughness measurements were made using needle profilometers (1 m long and with 2-cm sampling intervals). Ten roughness profiles were sampled for each training field (parallel and perpendicular to the row direction). From these measurements, the two roughness parameters, i.e., root mean square (rms) surface height and correlation length (L), were calculated using the mean of all correlation functions. The rms surface heights range from 1.1 to 3.3 cm, and the correlation length (L) varies from 2.3 cm in sown fields to 9.3 cm in plowed fields.

III. METHODOLOGY

The retrieval of soil moisture from TerraSAR-X images by means of empirical approaches requires the development of experimental relationships between $\sigma^\circ_{\mathrm{TerraSAR-X}}$ and the measured soil moisture. TerraSAR data acquired in two configurations of incidence angles ($\sim 26^\circ$ and $\sim 50^\circ$) were used with ground measurements conducted over bare soil. The sensitivity of TerraSAR signal to soil moisture is the greatest for low incidence angle (0.43 dB/% for 26°–28° and 0.29 dB/% for 50°–52°; Fig. 3). For a confidence level of 95%, there are significant relationships between the TerraSAR-X backscattering coefficient and the *in situ* soil moisture because the p-values are much less than 0.05 ($p\text{-}value < 2.2 \times 10^{-16}$ for HH26°–28° and $p\text{-}value = 1.52 \times 10^{-10}$ for HH50°–52°). AQ8

Studies using C-band (ERS, RADARSAT, ASAR, etc.) showed lower sensitivities between radar signal and soil moisture, between 0.2 and 0.3 dB/% for low incidence angles and about 0.1 dB/% for high incidence angles (e.g., [2] and [11]–[13]). AQ9

The objective of this study is to analyze the influence of incidence angle on the accuracy of the soil moisture estimate. Configurations in HH polarization with single incidence angle (26°–28° or 50°–52°) were studied. Next, multi-incidence TerraSAR-X images acquired at both low and high θ values with one-day-spaced dates and only minor variations in soil characteristics were used to analyze the possible improvement in the soil moisture estimates when two incidences are used.

The empirical relationship between the radar backscattering coefficient (σ°) and the volumetric soil moisture (mv) for bare soil surfaces without taking into account the rms surface height is given by (e.g., [14]; Fig. 3)

$$\sigma^\circ_{\mathrm{dB}} = f(mv, \theta)_{\mathrm{dB}} = \delta mv + \xi. \tag{2}$$

This simplified relationship is valid for mv values between 5% and 35% [6]. The coefficient δ is dependent on SAR parameters (radar wavelength, incidence angle, and polarization), while the coefficient ξ is controlled by SAR parameters and surface roughness. Experimental data of σ° and mv show slope δ values of about 0.43 dB/% for HH26°–28° and 0.29 dB/% for HH50°–52°.

The relationship obtained between σ° and the rms *height* independent of row direction, correlation length, and soil moisture could be written as an exponential relationship of the form $\sigma^\circ_{\mathrm{dB}} = g(rms, \theta)_{\mathrm{dB}} = \mu e^{-krms} + c$ [15], [16] or a logarithmic relationship of the form $\sigma^\circ_{\mathrm{dB}} = g(rms, \theta)_{\mathrm{dB}} = \mu \ln(rms) + c$ [1]. AQ10

With taking into account of both soil roughness and soil moisture, the radar signal in decibel scale may be written as

TABLE II
INVERSION MODELS FOR ESTIMATING SOIL MOISTURE AND STATISTICS ON THE VALIDATION OF THESE MODELS

TerraSAR-X data - HH	Calibration phase Model	R^2	Validation phase		
			Bias	std	RMSE
26°-28°	mv (%) = 2.31 $\sigma°_{dB}$ + 37.19	0.79	0.52	2.76	2.81
50°-52°	mv (%) = 3.43 $\sigma°_{dB}$ + 54.30	0.66	2.95	2.83	4.09
26°-28° and 50°-52°	mv (%) = 1.67 $\sigma°_{dB}$ (θ_{low}) + 0.55 $\sigma°_{dB}$ (θ_{high}) + 38.22	0.69	1.65	2.46	2.91

the sum of two functions that describe the dependence of the radar signal on soil moisture (f: linear) and surface roughness (g: exponential) (e.g., [1] and [4])

$$\sigma^{\circ}_{\mathrm{dB}} = f(mv, \theta)_{\mathrm{dB}} + g(rms, \theta)_{\mathrm{dB}} = \delta, mv + \mu, e^{-krms} + \tau \quad (3)$$

where k is the radar wavenumber (~ 2 cm^{-1} for TerraSAR-X).

This equation neglects the effect of the correlation length L on the backscattering coefficient. To take account of the correlation length, Zribi and Deschambre [1] proposed a new roughness parameter Zs, *defined by* rms^2/L, which is the product of the rms surface height and the slope of the soil surface (rms/L). Thus, the empirical model linking σ° and Zs could be written as $\sigma^{\circ}_{\mathrm{dB}} = \delta mv + \eta e^{-kZs} + \psi$.

In the case of one SAR image characterized by one incidence ($\theta = 26°–28°$ or $50°–52°$), inversion model is written as follows:

$$mv = \alpha \sigma^{\circ}(\theta) + \beta. \quad (4)$$

The use of two incidence angles eliminates the effects of roughness and thus allows linking the backscattering coefficient to the soil moisture only. For two images acquired with low and high incidence angles, the estimate of soil moisture can be obtained by solving (3) for two incidences (substituting the e^{-krms} of $\sigma^{\circ}(\theta_{\mathrm{low}})$ into $\sigma^{\circ}(\theta_{\mathrm{high}})$

$$mv = \alpha \sigma^{\circ}(\theta_{\mathrm{low}}) + \beta \sigma^{\circ}(\theta_{\mathrm{high}}) + \gamma. \quad (5)$$

α and β depend on δ and μ, whereas γ is a function of δ, μ, and τ (in both incidence angles).

The form of (5) should be the same if the Zs parameter was used.

The empirical models given in (4) and (5) were then fitted to experimental data acquired in 2008 and 2009 by using the least squares method (cf. Table II). The validation of these models was tested in using the data set of 2010 (13 points for each of the two configurations HH26° and HH50°). The inputs are the mean backscattering coefficients in decibels calculated for each reference field.

IV. RESULTS AND DISCUSSION

The inversion procedures were applied in order to retrieve soil moisture. The results obtained in the validation phase with one low incidence show inversion errors in the estimation of mv of about 3% for incidence angles. The use of high incidences (50°–52°) gives slightly poorer results with an rmse of about 4%. The accuracy of the soil moisture estimate remains unchanged by using TerraSAR-X multi-incidence data (both low and high incidence angles) with an rmse of about 3% (Table II). Fig. 4 shows the good agreement between estimated and measured mv values.

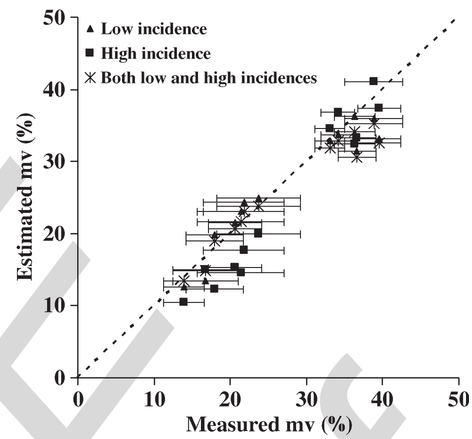

Fig. 4. Comparison between the estimated mv values and those measured. The error bars on the measured soil moisture values correspond to one standard deviation.

In contrast, large errors in the retrieved soil moisture were observed at C-band for a single incidence angle (rmses of about 6% for 20° and 9% for 40°) [4]. This is due to the fact that the radar signal is much more sensitive to surface roughness at high radar wavelength. The accuracy is strongly improved with the use of both low and high incidences (rmse of about 3.5%) (e.g., [1], [2], and [4]).

The dependence of the radar signal at X-band on surface roughness in agricultural areas was described as weak by several works ([8], [14], and [17]). Results of these studies show that the influence of surface roughness on the radar signal increases with increasing radar wavelength. Moreover, this dependence is mainly significant for low levels of roughness. At X-band, Baghdadi *et al.* [4], [8] showed that the sensitivity of σ° to surface roughness becomes weak for $rms > 1$ cm. Thus, the effect of surface roughness on radar signal becomes weak in X-band, which improves the estimates of soil moisture, particularly for $rms > 1$ cm. Moreover, the multi-incidence approaches become less effective because the effect of surface roughness that we try to eliminate is relatively weak at X-band compared to C-band.

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TABLE III
TERRASAR-X COVERAGE SIMULATION FOR ORGEVAL SITE BETWEEN SEPTEMBER 2 AND 12, 2010 (ORBIT CYCLE)

Time	02 sep.	03 sep.	04 sep.	05 sep.	06 sep.	07 sep.	08 sep.	09 sep.	10 sep.	11 sep.	12 sep.
θ (°)	-	39	58	50	26	-	26	50	58	39	-

V. CONCLUSION

This study examined the potential of TerraSAR-X data for estimating soil moisture (mv) over bare soils. TerraSAR-X images collected between 2008 and 2010 over two study sites in France were used. SAR images were acquired at HH polarization and for incidence angles of 26°, 28°, 50°, and 52°. The goal of this work was to compare estimates of mv obtained from various incidence configurations and to find the best sensor configuration in incidence angle for measuring the bare soil moisture.

This study tested empirical models for soil moisture inversion from one incidence (low or high) and multi-incidence TerraSAR-X data (both low and high incidences). The results of this study may be summarized as follows.

1) For a single incidence, the retrieval algorithm performed very well for low and high incidence angles. The rmses for the soil moisture estimate are about 3% for 26°–28° and 4% for 50°–52°.
2) The accuracy of the soil moisture estimate does not improve when two incidence angles (rmse is about 3%) are used.

These results appear promising for the development of simplified algorithms for retrieving soil moisture from TerraSAR-X data and for monitoring temporal moisture changes. Table III lists the different observation possibilities for the Orgeval study site within one orbit cycle (11 days). This site could be imaged 8 times within 11 days (two images for each following incidence: $\sim$ 26°, 39°, 50°, and 58°) and 24 times within one month. The soil moisture mapping frequency with low incidence angle (26°) or with both low and high incidence angles (26° and 50°) is possible six times within one month. The incidence of 39° can also be used, which would increase to 12 the TerraSAR-X scene number within one month. This very short revisit time makes TerraSAR-X a very useful source for the soil moisture mapping. Moreover, the increase in the acquisition frequency is much awaited for the soil moisture data assimilation in hydrological modeling.

In addition, the very high spatial resolution (metric) of the TerraSAR-X sensor is also very promising for local estimation of soil moisture at the within agricultural field scale. It offers a great potential in terms of improving the quality of soil moisture mapping for catchment areas where the parcels are of small size.

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REFERENCES

[1] M. Zribi and M. Dechambre, "A new empirical model to retrieve soil moisture and roughness from C-band radar data," *Remote Sens. Environ.*, vol. 84, no. 1, pp. 42–52, Jan. 2003.

[2] H. S. Srivastava, P. Patel, M. L. Manchanda, and S. Adiga, "Use of multi-incidence angle RADARSAT-1 SAR data to incorporate the effect of surface roughness in soil moisture estimation," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 7, pp. 1638–1640, Jul. 2003.

[3] Y. Oh, "Quantitative retrieval of soil moisture content and surface roughness from multipolarized radar observations of bare soil surfaces," *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 3, pp. 596–601, Mar. 2004.

[4] N. Baghdadi, N. Holah, and M. Zribi, "Soil moisture estimation using multi-incidence and multi-polarization ASAR SAR data," *Int. J. Remote Sens.*, vol. 27, no. 10, pp. 1907–1920, 2006.

[5] A. K. Fung, *Microwave Scattering and Emission Models and Their Applications*. Boston, MA: Artech House, 1994, 573 pages.

[6] H. Holah, N. Baghdadi, M. Zribi, A. Bruand, and C. King, "Potential of ASAR/ENVISAT for the characterisation of soil surface parameters over bare agricultural fields," *Remote Sens. Environ.*, vol. 96, no. 1, pp. 78–86, May 2005.

[7] F. T. Ulaby, P. P. Batlivala, and M. C. Dobson, "Microwave backscatter dependence on surface roughness, soil moisture, and soil texture: Part I—Bare soil," *IEEE Trans. Geosci. Electron.*, vol. GE-16, no. 4, pp. 286–295, Oct. 1978.

[8] N. Baghdadi, M. Zribi, C. Loumagne, P. Ansart, and T. Paris Anguela, "Analysis of TerraSAR-X data and their sensitivity to soil surface parameters over bare agricultural fields," *Remote Sens. Environ.*, vol. 112, no. 12, pp. 4370–4379, Dec. 2008.

[9] M. Aubert, N. Baghdadi, M. Zribi, A. Douaoui, C. Loumagne, F. Baup, M. El Hajj, and S. Garrigues, "Analysis of TerraSAR-X data sensitivity to bare soil moisture, roughness, composition and soil crust," *Remote Sens. Environ.*, vol. 115, no. 8, pp. 1801–1810, Aug. 2011.

[10] T. Fritz, TerraSAR-X Ground Segment Level 1b Product Format Specification (10.12.2007), p. 257, 2007, Issue, 1.3, Doc.: TX-GS-DD-3307. [Online]. Available: http://www.dlr.de/tsx/documentation/TX-GS-DD-3307_Level-1b-Product-Format-Specification_1.3.pdf AQ11

[11] N. Baghdadi, O. Cerdan, M. Zribi, V. Auzet, F. Darboux, M. El Hajj, and R. Bou Kheir, "Operational performance of current synthetic aperture radar sensors in mapping soil surface characteristics: Application to hydrological and erosion modeling," *Hydrol. Process.*, vol. 22, no. 1, pp. 9–20, Jan. 2008.

[12] S. Le Hégarat-Mascle, M. Zribi, F. Alem, A. Weisse, and C. Loumagne, "Soil moisture estimation from ERS/SAR data: Toward an operational methodology," *IEEE Trans. Geosci. Remote Sens.*, vol. GRS-24, no. 12, pp. 2647–2658, Dec. 2002.

[13] A. Quesney, S. Le Hégarat-Mascle, O. Taconet, D. Vidal-Madjar, J. P. Wingneron, C. Loumagne, and M. Normand, "Estimation of watershed soil moisture index from ERS/SAR data," *Remote Sens. Environ.*, vol. 72, no. 3, pp. 290–303, Jun. 2000.

[14] F. T. Ulaby, R. K. Moore, and A. K. Fung, *Microwave Remote Sensing, Active and Passive, From Theory to Applications*, vol. 3. Norwood, MA: Artech House, 1986, 1098 pages.

[15] Y. Oh, K. Sarabandi, and F. T. Ulaby, "An empirical model and an inversion technique for radar scattering from bare soil surfaces," *IEEE Trans. Geosci. Remote Sens.*, vol. 30, no. 2, pp. 370–381, Mar. 1992.

[16] N. Baghdadi, C. King, A. Bourguignon, and A. Remond, "Potential of ERS and RADARSAT data for surface roughness monitoring over bare agricultural fields: Application to catchments in Northern France," *Int. J. Remote Sens.*, vol. 23, no. 17, pp. 3427–3442, 2002.

[17] N. Baghdadi, N. Holah, P. Dubois, L. Prévot, S. Hosford, A. Chanzy, X. Dupuis, and M. Zribi, "Discrimination potential of X-band polarimetric SAR data," *Int. J. Remote Sens.*, vol. 25, no. 22, pp. 4933–4942, 2004.

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